

NAL PROPOSAL No. 0071

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A MEASUREMENT OF THE PION RADIUS

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## ABSTRACT

We propose a wire spark chamber experiment to measure the pion electromagnetic radius accurate to  $\pm 0.03f$  by measuring the scattering cross section for 50--80 GeV pions from electrons in a liquid hydrogen target. The data will distinguish between the  $\rho$  dominance prediction of  $0.64f$  and the "proton-like" radius to  $0.81f$ .

## II. PHYSICS JUSTIFICATION

The electromagnetic dimensions of the various particles are of fundamental interest. The charge radius of both the pion and proton are predicted to be 0.64f from rho-dominance, yet the proton radius measured from electron-proton scattering is 0.81f. A measurement of the pion radius is crucial in order to understand whether this difference is due to some peculiarity of the nucleon or to a breakdown of vector dominance. In a larger sense, this is one place where theory has far out-stripped experiment. The pion radius is one of the fundamental numbers of physics and has inspired a wide variety of theoretical predictions only loosely subjected to experimental test. Many of these predictions fail to differentiate between "proton-like" (0.81f) and "rho-dominance" (0.64f) radii. Recent speculation<sup>1</sup> has suggested that the pion radius may be even smaller if higher mass particles couple to the photon. This experiment will differentiate among these values for the radius by measuring cross sections to a precision of one per cent. This accuracy distinguishes between the two values of 0.64f and 0.81f by six standard deviations and rejects a point-like pion by about fifteen standard deviations.

We will measure the cross section differential in the final state electron energy. This is given in terms of the point cross section by

$$\frac{d\sigma}{dE} = \left( \frac{d\sigma}{dE} \right)_{\text{point}} f_{\pi}^2$$

where  $f_{\pi}$  is the pion form factor. Since the momentum transfer is small in

pi-e collisions,  $f_\pi$  depends only on the mean radius,  $\langle r_\pi \rangle$  and,  $q^2$ , the four momentum-transfer squared:

$$f_\pi \approx 1 + \frac{1}{6} q^2 \langle r_\pi \rangle^2$$

Direct pi-e scattering has been measured in several experiments. The most accurate completed experiment<sup>2</sup> quotes  $\langle r_\pi \rangle < 3 \times 10^{-13}$  cm. A Dubna group led by E. Tsyganov is scheduled to carry out an experiment whose aim is to measure the radius with a 50 GeV/c  $\pi^-$  beam and a wire-spark-chamber spectrometer. Even if the Serpukhov experiment is successful, the added intensity and improved techniques of this proposed experiment will provide a more accurate result with less systematic error. A group from Harvard led by Richard Wilson has proposed to do the experiment at the AGS with a pion beam of about 25 GeV/c. The effect to be measured in the present experiment is at least a factor of three larger. Table I compares the effect expected in the cross section for three incident pion beam energies representative of the three experiments. The AGS experiment would run at 25 GeV, the Serpukhov experiment at 50, and this experiment at both 50 and 80 GeV. We use the previous equations,  $q^2 = 2m_e^2 - 2m_e E_e$  and  $q_{\max}^2 = \frac{4m_e p_\pi^2}{m_e^2 + m_\pi^2 + 2m_e E_\pi}$  where  $p_\pi$ ,  $E_\pi$  refer to the initial pion;  $m_e$  and  $m_\pi$  are the electron and pion mass; and  $E_e$  is the final state electron energy.

pion beam energy	range of accepted recoil electron energy	% deviation from the point cross section	
		$\langle r_{\pi} \rangle = 0.81f$	$\langle r_{\pi} \rangle = 0.64f$
80 GeV	40 -- 64 GeV	23 -- 36	14.5 -- 23
50	25 -- 37.5	13.5--21.5	8.5 -- 13.5
25	8 -- 14	4.7-- 8.0	2.9 -- 5.2

Three other methods have been used to measure the pion form factor. Berkelman et al.<sup>3</sup> and Mistretta et al.<sup>4</sup> isolated the one-pion exchange diagram in  $\pi^+$  electroproduction and measured its contribution as a function of  $q^2$  to extract  $\langle r_{\pi} \rangle$ . They find  $\langle r_{\pi} \rangle \approx 0.8 \pm 0.1f$  but the result is uncertain theoretically because of the difficulty in estimating the contribution of other terms to the cross section. Block et al.<sup>5</sup> use  $\pi^+ - \text{He}^4$  elastic scattering to find the pion form factor via an interference effect. They find  $\langle r_{\pi} \rangle < 1 \times 10^{-13} \text{ cm}$ . This method also suffers from significant uncertainty due to the contribution of terms other than Coulomb scattering. The third method is via colliding beams. These elegant experiments measure the form factor in the time-like region so that a measurement of the form-factor in the space-like region provides an opportunity to test the ability to extrapolate to short distances. At the present time, if the electroproduction experiments are correct, this extrapolation fails<sup>6</sup> as can be seen in Fig. 1.

We choose 50 and 80 GeV to perform this experiment because

- 1) The effect in the cross section is larger than at lower energies.
- 2) Backgrounds leading to systematic errors can be suppressed via longitudinal momentum balance at these energies. This might not be possible at higher energies.  $\pm 0.1\%$  resolution in incoming and

outgoing momenta permit balance to  $\pm 120$  MeV at 80 GeV, sufficient to reject backgrounds in the final state from strong interaction by two standard deviations.

- 3) Counting rates decrease with energy but are still more than adequate.
- 4) Systematic effects in efficiencies are energy independent and their effect is less pronounced than at lower energies.

### III. EXPERIMENTAL DETAILS

#### Introduction

A diagram of the experimental layout is shown in Fig. 2. The apparatus is situated in the medium-energy high-resolution charged beam (MEHR). A flux of  $3 \times 10^6$  charged pions/pulse is incident on a 50cm liquid hydrogen target. The momentum and scattering angles of the recoiling  $\pi$ -e pair are measured with a combination of proportional chambers, magnetostrictive-wire chambers and a spectrometer magnet. Differentiation between pions and electrons is accomplished with total absorption shower counters. The trigger consists of two charged particles within a 10 msr-scattering cone, defined by scintillation counter  $S_1$ , which also pass into appropriate momentum intervals defined by scintillation counters  $S_2$  and  $S_4$ . The particle momenta accepted by the apparatus at 50 and 80 GeV/c are shown below.

Incident Momentum	Pion Range	Electron Range
50 GeV/c	12.5 -- 25 GeV/c	25 -- 37.5 GeV/c
80 GeV/c	16 -- 40 GeV/c	40 -- 64 GeV/c

Charged particle background from the hydrogen target is rejected in the trigger by the anti-coincidence counter A1. Muon triggers are rejected by means of a bank of anti-coincidence counters behind a steel wall.

We will run the experiment with negatively and positively charged pions at 50 GeV/c and with negative pions at 80 GeV/c. Positive pions will be used to test for charge dependent systematic effects, while the 80 GeV/c data will determine energy dependent systematic effects. With an incident  $\pi^-$  beam, a single spectrometer arm behind the magnet is necessary. In Figure 2, this consists of wire chambers SC 1-4, scintillation counters S2 and S4, shower counters S3 and S5, and the muon telescope. The magnet polarity is set appropriately to bend negatively charged particles into this arm. With an incident  $\pi^+$  beam, the magnet polarity is reversed such that negatively charged particles are bent in the opposite direction and a double arm spectrometer is used. The additional arm now detects the recoil electron and consists of wire chambers SC 5-8, and scintillator S2 with shower counter S3 taken from the original arm. S5 is also removed from the original arm which now detects only  $\pi^+$  and  $\mu^+$ .

### Resolution

Adequate momentum resolution is obtained by spacing the chambers before and after the spectrometer magnet over a 10 meter interval and by requiring the field integral for the spectrometer magnet to be 100 kgauss-meters. The momentum resolution is then given approximately by

$$\frac{\Delta p}{p} = 1.1 \times 10^{-4} (.045 p^2 + 31)^{1/2}$$

where  $p^2$  is in  $(\text{GeV}/c)^2$ .

The momentum dependent term is based upon a 0.5 mm spark resolution, the momentum independent term comes from multiple scattering. The terms are approximately equal at 25 GeV/c where the resolution is  $\pm 0.1\%$ . Multiple scattering diminishes in importance at higher energies. At 50 GeV/c the momentum balance can be done at a precision such that  $\Delta E_f = \pm 50$  MeV.

The horizontal aperture of the magnet should be 48" in order to accept the wide momentum range of the final state. A 10" gap is adequate for a 10 msr acceptance in the vertical direction. A hodoscope placed at the momentum slit of the incident pion beam will serve to define the incident pion energy to  $\pm 0.1\%$  so that at 50 GeV/c,  $\Delta E_i = 50$  MeV. The longitudinal momentum balance will be  $\pm 80$  MeV at 50 GeV/c and  $\pm 120$  MeV at 80 GeV.

#### Event Rate

Our estimates of running time are based on the following considerations. The Bhabha cross section is given by

$$\frac{d\sigma}{dE} = \frac{2 m_e r_o^2}{E^2} \left( 1 - \frac{E}{E_m} \right) \quad \begin{array}{l} \text{where } E = \text{energy of outgoing} \\ e^- \text{ and } E_m \text{ is its maximum} \\ \text{value} \end{array}$$

Electrons are accepted between 25 and 37.5 GeV for the 50 GeV case, thus

$$\begin{aligned} \sigma &= 25.5 \times 10^{-29} \int_{25}^{37.5} \frac{d\sigma}{dE} dE \\ &= 0.645 \mu\text{b} \end{aligned}$$

For 100% geometric efficiency and a 50cm hydrogen target, the yield is

$$Y = 1.4 \times 10^{-6} \text{ per incident pion.}$$

At 50 GeV we will run the beam at  $3 \times 10^6$  negative pions per pulse, the event trigger rate being

$$T_e = 1.4 \times 10^{-6} \times 3 \times 10^6 \approx 4 \text{ per pulse}$$

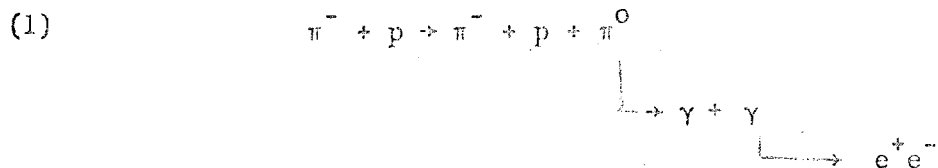
The  $\pi^-$  flux at 80 GeV will be lower, we expect only  $10^6$  per pulse. The 50 GeV  $\pi^+$  beam contains 60% protons so we will limit its intensity to  $10^6$   $\pi^+$  per pulse. Running time would be proportioned as follows:

50 hours	checkout
40 hours (100,000 counts)	50 GeV $\pi^-$
60 hours ( 50,000 counts)	80 GeV $\pi^-$
<u>60 hours</u> ( 50,000 counts)	50 GeV $\pi^+$
210 hours	

In order to accept  $3 \times 10^6$  negative pions/pulse at 50 GeV/c we will use proportional chambers to define the trajectories of the incident pion and the recoiling pi-e pair. The proportional chambers upstream of the hydrogen target will also be used as beam counters. In the rear of the magnet, where beam loading can be avoided and where an increased area is involved, magnetostrictive-wire chambers will be used.

## Backgrounds

We consider two background processes at 50 GeV for the  $\pi^+e^-$  detection configuration only. The first is



Here a  $\gamma$  ray from the  $\pi^0$  converts to an  $e^+e^-$  pair, the  $\pi^-$  and  $e^-$  simulating a scattering event. The yield from this reaction has been calculated by the Dubna group<sup>7</sup> by assuming that the yield of secondaries from incident pions is the same as that from incident protons. The very small solid angle of the  $\pi$ -e process is of great importance in rejecting these strong interactions backgrounds. The probability per incident pion that the  $\pi^-$  and  $\pi^0$  be produced in the appropriate solid angle and momentum interval is

$$P = P_{\pi^-} \cdot P_{\pi^0}$$

where  $P_{\pi^0}$  and  $P_{\pi^-}$  are the separate probabilities for the  $\pi^0$  and  $\pi^-$ . They find the probability to be

$$P = 10^{-3} \times 10^{-3} = 10^{-6} \text{ per incident pion}$$

The probability of conversion of a  $\gamma$  ray with an  $e^-$  energy in the triggering range is  $10^{-2}$ . The anti-coincidence counter around the target should further reduce this background at least a factor of  $10^{-1}$  as estimated by a Monte Carlo calculation performed at UCLA. The expected yield is  $10^{-6} \times 10^{-2} \times 10^{-1} = 10^{-9}$  per incident pion. Coplanarity and opening angle cuts reduce this background in analysis by another factor of  $10^{-2}$ . With an event yield of  $1.4 \times 10^{-6}$ , this background ratio is

$$B = \frac{10^{-9} \times 10^{-2}}{Y} = \frac{10^{-11}}{1.4 \times 10^{-6}}$$

and is negligible. The expected trigger rate for this background in a beam of  $3 \times 10^6$  pions is

$$T_b = 10^{-9} \times 3 \times 10^6 = 3 \times 10^{-3} \text{ per pulse}$$

The second background process that we have considered is



Here one  $\pi^-$  is incorrectly interpreted as an  $e^-$ . The  $\pi^-\pi^-$  yield calculated by the Dubna group into the solid angle and momentum acceptance is expected to be

$$P = 3 \times 10^{-4} \quad \text{per incident pion}$$

Because of this high yield we have performed a Monte Carlo calculation for this reaction. The program was based upon

- 1) peripheral  $\Delta^{++}$  production,
- 2) phase space for the  $\pi^-\pi^-$  pair,
- 3) the  $\pi^+p$  (treated as a Breit-Wigner resonance) of mass 1238 MeV.

We find that the anti-coincidence counter (either the  $\pi^+$  or the proton were required to traverse more than 2" of hydrogen) around the target is extremely effective. Of 100,000 events thrown,  $63 \times 10^3$  would normally have triggered the apparatus, but only 37 survived the anti coincidence. Considering counter inefficiencies, we assume  $10^{-2}$  rejection for this anti-coincidence. Furthermore, coplanarity, opening angle, and longitudinal momentum balance cuts reduce these 630 events further. Thus only five candidates are left after analysis. Shower counter identification of the electron should reduce this by an additional factor of  $10^{-2}$ . We find for the background ratio

$$B = 3 \times 10^{-4} \times \frac{5}{63 \times 10^3} \times 10^{-2} \times \frac{1}{Y}$$

$$= 1.7 \times 10^{-4}$$

and for the trigger rate (we assume no rejection by the shower counter in the trigger)

$$T_b = 3 \times 10^{-4} \times 10^{-2} \times 3 \times 10^6$$

$$= 9 \text{ per pulse}$$

We estimate all other backgrounds to be small. Proton and kaon scatters cannot be confused with  $\pi$ -e scattering events because the kinematics are completely different. Electron contamination in the beam can be determined by looking above the kinematic energy allowed by  $\pi$ -e kinematics or by inserting Pb in the beam to alter the  $\pi$  to e ratio;  $\mu$ -e scatters are eliminated by muon identification. One could use these muon events for normalization in the experiment although the statistics will be limited ( $\approx 2,000$  events).

#### Radiative corrections

The radiative corrections to this experiment must be accurate because absolute cross sections will be measured to  $\pm 1\%$  accuracy. Such corrections depend upon the details of the experiment and we have not yet calculated them precisely. In principle, they are, exactly calculable if the experimental resolution is well-known; so that no fundamental problems are expected. We can estimate the size of these corrections using the notation  $\sigma = \sigma_{\text{exp}}(1 + \sum \delta_i)$  where the  $\delta_i$  are found as follows.

For a 0.2% momentum resolution of the outgoing particle, the bremsstrahlung correction for 25cm of hydrogen is

$$\delta_B = \tau \int_{E_{\min}}^{E_{\max}} \frac{dK}{K}$$

where K is the photon energy and  
 $\tau$  is the radiator thickness

$$\approx 0.025 \ln \frac{35 \text{ GeV}}{35 \text{ MeV}}$$

$$= 0.0155$$

The Landau loss for the particles in the target is small because the momentum balance is uncertain to  $\approx 50 \text{ MeV}$

$$\delta_L = \frac{\xi \ell}{\Delta E}$$

$$\text{where } \xi \approx 10^{-2}$$

$$\ell \approx 25 \text{ cm}$$

$$\approx 0.005$$

$$\Delta E = 50 \text{ MeV}$$

Radiative corrections have been estimated by Bardin et al.<sup>8</sup> and by Kahane.<sup>9</sup>

There are three contributions.  $\delta_1$  is the elastic one-photon exchange contribution.

$$\delta_1 = \frac{\alpha}{\pi} \left[ \frac{13}{6} \ln \frac{q^2}{\pi^2} + \frac{2(K' + 1)}{a'} \ln \frac{a' + K'}{a' - K'} - \frac{46}{9} \right]$$

where

$$K' = \frac{q^2}{2m_\pi^2}$$

$$a' = (K'^2 + 2K')^{1/2}$$

At 50 GeV and maximum momentum transfer, this term is

$$\delta_1 = -0.55$$

$\delta_2$  is the elastic two-photon exchange contribution. Since it is small, we ignore its contribution for this discussion.

$$\delta_2 \approx 0$$

The third contribution  $\delta_3$  is from diagrams with external photon lines. This correction depends on the experimental resolution. We approximate this result by considering only those terms dependent upon momentum resolution and by ignoring the angular measurements. The resulting expression is lengthy but gives approximately

$$\delta_3 = 0.15$$

for our experimental conditions.

The total correction is

$$\delta = \delta_B + \delta_L + \delta_1 + \delta_2 + \delta_3$$

$$\delta \approx 0.255$$

The uncertainty in the correction depends in principle only on the knowledge of our experimental resolution and this will be studied in detail in the course of the experiment.

#### IV. APPARATUS

The major components of the apparatus shown in Fig. 2 are as follows:

- 1) A liquid-hydrogen target 50cm long.
- 2) An analyzing magnet with a field integral of 100 kgauss-meters.
- 3) Seven proportional chambers and four magnetostrictive chambers.
- 4) Two total absorption Cherenkov shower counters for particle identification.
- 5) A muon wall for muon rejection.
- 6) Scintillation counters for triggering purposes and for anti-coincidence around the liquid-hydrogen target.
- 7) A differential Cherenkov counter for tagging beam pions.

We will require that NAL supply the analyzing magnet, the liquid hydrogen target, and the differential Cherenkov counter. The magnet should be approximately five meters in length with a peak field of  $\approx 20$  Kg. The downstream limiting aperture should be 48" horizontally by 10" vertically. It would be acceptable to break the magnet into two separate magnets. In this case the aperture of the upstream magnet could be reduced to about 8" x 24". The liquid hydrogen target should be 3cm in diameter and 50cm long. It must have an accurately known density and length.

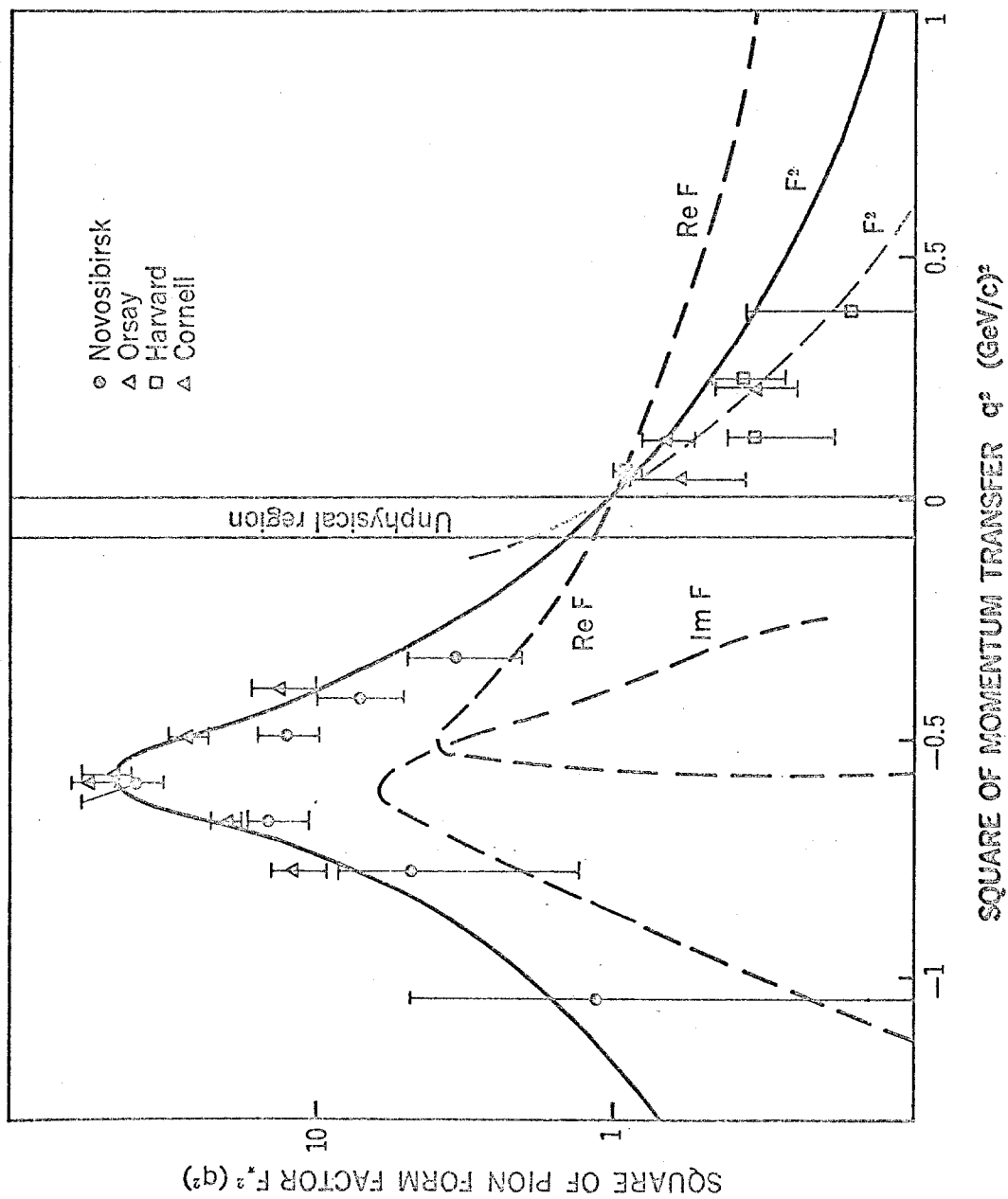
We will supply our own on-line computation in the form of a Hewlett-Packard 2116B computer. However, we would like to tie this into a larger computer for an additional floating-point facility if one is available. The apparatus requires no scanning facilities.

We will also require from NAL the fast electronics to form a trigger. UCLA will supply the remainder of the apparatus including the electronics for the proportional chambers. They will have an active volume of 30cm by 30cm. Since the downstream chambers are large (1m x 2m), they will be "conventional" wire chambers with magnetostrictive readout. In order to use them effectively the area of the incident pion beam will be deadened.

All equipment will be ready in June, 1972. We will require of NAL the usual support facilities involved in the setup and running of an experiment.

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PION FORM FACTOR (squared) in both time-like and space-like regions. Data from four laboratories is compared to the vector-dominance model (black lines; solid line is  $F^2$ , dashed lines are  $\text{Re } F$  and  $\text{Im } F$ ). Colored line is proportional to the nucleon form factors. Vector-dominance model has a single resonance and has small adjustments to satisfy analyticity requirements.

FIGURE 1

# EXPERIMENTAL LAY-OUT FOR PION-ELECTRON SCATTERING

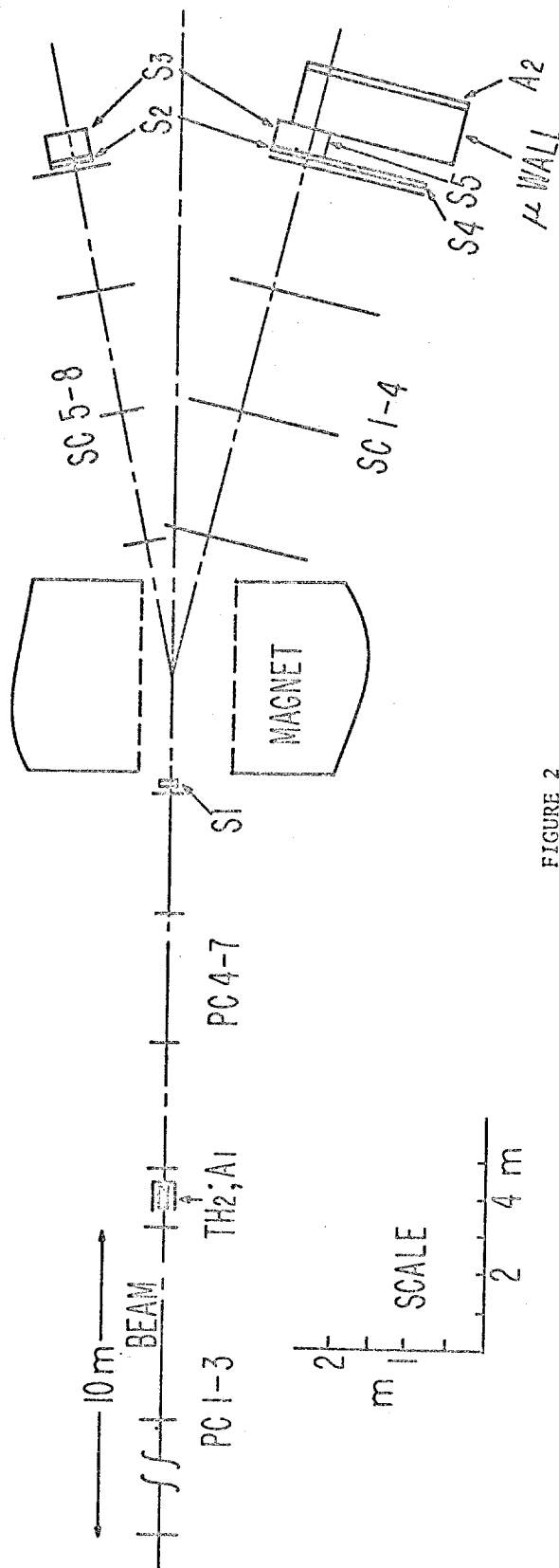


FIGURE 2

PC 1-7 are proportional chambers; SC 1-8 are magnetostriuctive wire chambers; TH<sub>2</sub> is the liquid-hydrogen target; A<sub>1</sub> is the anti-coincidence counter for the target; S<sub>1</sub> is a scintillator which defines the acceptance; S<sub>2</sub> and S<sub>4</sub> are scintillators which detect the pion and electron; S<sub>3</sub> and S<sub>5</sub> are shower counters; A<sub>2</sub> is an anti-coincidence counter for muon rejection.



DEPARTMENT OF PHYSICS  
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June 25, 1971

Dr. James Sanford  
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Dear Jim:

I am writing you with regard to our Proposal No. 71, pion-electron scattering in light of our recent experience at Serpukhov. This letter reaffirms the interest of the UCLA group in the experiment at NAL and is notification that we would like to have our proposal reconsidered at this time. A description of the experiment as we now envision it is included with this letter. Proposal 71 was submitted before the Serpukhov collaboration was approved, and its objectives have now been met, i.e. the Serpukhov experiment has measured the pion radius. We now propose an experiment in an unseparated 300 GeV beam in order to measure the curvature of the pion form factor and simultaneously the kaon radius. The experiment could be done as early as January 1972 but we prefer to do it in summer 1972.

Two of our Dubna collaborators are included in the proposal even though the status of such a collaboration is uncertain. We have also discussed the question of a collaboration with John Poirier and Gene Engles; these discussions are continuing.

#### Serpukhov Results

The features of the Serpukhov data relevant to the NAL schedule are the following.

1. At 50 GeV, the pion-electron signal is amazingly clean provided that both the pion and electron are measured. Application of three constraints (without electron identification) leaves only about a 0.25% strong interaction background. We conclude that the experiment can easily be extended to higher energies.
2. We have taken 13,000 events with  $q^2 > 0.025$  and 50,000 with  $q^2 > 0.014$ . In addition we have a final run in July. The statistical error on the cross section is less than 1%; on the pion radius less than 5%. We conclude that another experiment in the 50-100 GeV region will be only a repetition of an experiment already completed.

3. No K-e scatters were recorded, the maximum recoil electron energy being below our 12 GeV cutoff.

The pion form-factor at NAL

We believe that the next experiment should be done using a beam of order 300 GeV. In such an experiment, the radius will be accurately measured by the low  $q^2$  events and the curvature of the form factor by high  $q^2$  events. The attached proposal shows that differences in the cross section at  $q^2 = 0.2(\text{GeV}/c)^2$  due to different models of the form factors are of order 5%. In order to distinguish models even at this high energy, a precise experiment is required. An experiment at lower energy must be inordinately accurate in order to generate physics not already known from the Serpukhov experiment.

The kaon form factors

In a 300 GeV experiment, recoil electrons would be accepted in the range 75 GeV - 225 GeV. Electrons from K-e scattering from 75 GeV to the kinematic limit 167 GeV would be recorded. Kaon identification in the beam would be used but the scattering angles alone are, in principle, sufficient to distinguish between  $\pi$ -e and K-e scattering. Such an experiment should measure the K radius accurate to about  $\pm 10\%$ .

Cross Section and Beam Intensity

It is interesting that the cross section as measured from 1/2 the beam energy to the kinematic maximum varies slowly with beam energy. It is 0.60  $\mu\text{barns}$  at 50 GeV and 0.22  $\mu\text{barns}$  at 300 GeV. Thus beam intensities of order  $10^6$  and a magneto-strictive chamber experiment give enough counts in a reasonable running time.

I hope these comments are of some use to you in determining which particle-electron scattering investigations should be done at NAL. As you can see, my personal biases are understandably strong.

Sincerely,

*Darrell Drickey*

Darrell Drickey

DD:jw

cc: W.K.H. Panofsky

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Appendix to Proposal 71

A MEASUREMENT OF THE PION FORM FACTOR

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June 1971

## Appendix to Proposal 71

### A measurement of the pion form-factor

June 1971

#### Abstract

The UCLA group is currently completing a pion-electron scattering experiment at Serpukhov using 50 Gev  $\pi^-$  beam. The objectives of the Serpukhov experiment are the same as those of Proposal 71, in fact, proposal 71 was submitted before approval of the Serpukhov experiment. We feel that the objectives of these two proposals have been met, that is, the pion radius has been adequately measured and any further low-energy experiment would be only a repetition. Furthermore we find that  $\pi^- e$  events can be rather easily separated from strong interaction backgrounds. For these reasons we now propose an experiment at 300 Gev to measure the curvature in the pion form factor and to measure the kaon charge radius, using magnetostriuctive spark chambers in a beam of about  $10^6 \pi^-$  / burst.

## Serpukhov results

Our experiment at Serpukhov has directly lead to the changes in Proposal 71 presented in this Appendix.

The relevant features of the Serpukhov experiment are as follows.

1. At 50 GeV the pion-electron signal is amazingly clean as can be seen in Figure 1 provided that the scattering angles are well measured (0.1 mr) and momenta adequately measured ( $\pm 2\%$ ). Figure 1 shows application of 3 constraints to 17,145 raw events (pairs) taken without a shower counter in the system. Application of cuts on coplanarity, longitudinal momentum, and transverse momentum to the data leave clean pi-e events with an estimated 0.25% strong interaction background. Electron identification should reduce this background by another factor of 50 to 100. In these data we successfully identify the electron and pion by scattering angle only. We conclude that an experiment that applies three constraints to the data can be extended to energies much higher than 50 GeV.
2. In the Serpukhov experiment, we have taken 13,000 events with  $q^2 > .025 \text{ (GeV/c)}^2$  and 50,000 with  $q^2 > .014 \text{ (GeV/c)}^2$ . In addition, we have a final run during July, 1971. These data will give a statistical error of less than 5% on the pion radius. We do not yet know our systematic errors, but all indications are that they should also be of order 5%. Thus a further experiment to measure only the radius does not seem warranted unless we find some dramatically unexpected value for the size of the pion.

3. The maximum recoil electron energy from K-e scattering was below our 12 GeV cutoff so that no K-e scatters were recorded in the experiment.
4. All events were taken with a  $\pi^-$  beam; we can see no compelling reason to use positive beams. In fact, the equipment can be smaller and thus cheaper if the recoil pion and electron bend the same direction.

#### Physics Justification

In the opinion of the UCLA group, the next experiment on pi-e scattering should be done at very high energy with the intention of measuring the form factor curvature. Specifically we choose 300 GeV for the physics reasons outlined below and because of the apparent success of the 50 GeV Serpukhov experiment.

The pion form factor, regardless of its "true" theoretical form can be expanded phenomenologically

$$F_{\pi} = 1 + a q^2 + b q^4$$

The coefficient a is related to the pion radius

$$\langle r_{\pi} \rangle^2 = 6 a$$

Note that a 20% measurement of a is a 10% measurement of the radius.

The coefficient b is related to the curvature. Table I lists the values for a and b from four models of the pion form-factor.

TABLE I

$$F(q^2) = 1 + a q^2 + b q^4$$

model	- a	b
$F_{VDM} = \frac{1}{1 + q^2/m_p^2}$	$1.71 \text{ GeV}^{-2}$	$2.92 \text{ GeV}^{-4}$
$F_{VDM} \text{ (Finite width)}$	$1.45 - 2.07 \text{ GeV}^{-2}$	$(3.40 - 3.69) \text{ GeV}^{-4}$
$F_{\text{dipole}} = \frac{1}{(1 + q^2/2m_p^2)^2}$	$1.71 \text{ GeV}^{-2}$	$2.19 \text{ GeV}^{-4}$
$F_{\text{proton}} = \frac{1}{(1 + q^2/.71)^2}$	$2.82 \text{ GeV}^{-2}$	$5.92 \text{ GeV}^{-4}$

$$F_{VDM} = 1 - \frac{q^2}{m_p^2} + \frac{q^4}{m_p^4}$$

$$F_{\text{dipole}} = 1 - \frac{q^2}{m_p^2} + \frac{3q^4}{2m_p^4}$$

$$F_{\text{proton}} = 1 - \frac{2q^2}{.71} + \frac{3q^4}{(.71)^2}$$

$$F_{VDM}^* \text{ (Finite width)} = 1 - \frac{q^2}{\pi} \int_{4m_\pi^2}^{\infty} \frac{\text{Im } F_\pi(s) ds}{s^2} + \frac{q^4}{\pi} \int_{4m_\pi^2}^{\infty} \frac{\text{Im } F_\pi(s) ds}{s^3}$$

\* Integrals evaluated by Sakurai and Cho

We can estimate the effect in the cross section due to the coefficient b assuming that the low momentum transfer events accurately measure a.

$$\sigma = \sigma_0 F_\pi^2 \approx \sigma_0 (1 + bq^4)^2$$

$$\frac{\Delta\sigma}{\sigma} = 2 b q^4$$

At Serpukhov ( $q^2 = .03$ ) this term is 1.2% in the cross section if the pion is proton-like. Conceivably, we can see a one standard deviation effect due to b.

In order to differentiate models at this energy one must make a more accurate measurement. At 200 GeV recoil electron energy

$$\frac{\Delta\sigma}{\sigma} = .08 b$$

The smallest difference in the models is about  $\Delta b = 0.7 \text{ GeV}^{-4}$  corresponding to a 5.6% effect in the cross section. Thus a 300 GeV experiment comparable in accuracy to the Serpukhov experiment can distinguish these models and make a fundamentally new contribution to particle form factors.

#### The kaon form factor

A high energy experiment will also simultaneously measure the kaon radius. The pion experiment would accept recoil electrons in the energy range 75 GeV to 225 GeV but kaon-electron scattering is kinematically limited to 167 GeV maximum recoil electron energy ( $q^2 = 0.167$ ). We estimate that the kaon radius can be measured to  $\pm 10\%$  or better. Kaon identification in the beam would be used although the measurement of scattering angles alone is, in principle, sufficient to differentiate pi-e and K-e scattering.

## Experimental Details

Proposal 71 must be modified in some details for this higher energy experiment. In particular we propose using magnetostrictive chambers instead of proportional chambers (although some proportional chambers will be used). The apparatus is shown in Figure 2 and has been only slightly modified from the original Proposal 71, the major difference being the use of magnetostrictive chambers and a smaller magnet. The position and incident angle of the 300 GeV beam is measured in a block of 5 chambers upstream from the 50 cm liquid hydrogen target. The scattering angles of the pion and electron are measured in a second block of 7 spark chambers and then pass through a 30 cm x 40 cm x 3 m analysing magnet. Bending angles are measured in a block of chambers placed behind the magnet. Electrons and muons are identified by a shower counter and muon filter respectively. The trigger consists of a beam particle, a pair as defined by proportional chambers PC1-4 after the target and two particles in the scintillators  $S_2$  and  $S_4$ .

Angular resolutions of  $\pm 0.03$  mrad should be obtained and appear more than adequate to remove strong interaction backgrounds. Momentum resolution will be worse than proposed in Proposal 71 because the 50 GeV data suggest no need for precise resolution. Thus the magnet can be made much smaller and hence is less expensive.

A 300GeV unseparated beam is required; it is an advantage if it also contains a significant number of muons or if a muon beam is also available because the mu-e scatters provide a convenient normalization.

### Magnet

We will require a magnet of dimension approximately 30 cm x 50 cm x 3 m capable of a field of at least 18 Kg. We estimate the cost of such a magnet as less than \$50K although it is conceivable that two 18 D72 magnets could be modified to suit the experiment provided that they are available.

### Time Ready

The experimental equipment could be installed and the experiment started as early as January 1972. We prefer to do the experiment in summer 1972.

### Event Rate

The point cross section for pi-e scattering from 1/2 the beam energy to the maximum kinematic limit is  $0.645 \mu b$  in Proposal 71 (50 GeV). The corresponding value at 300 GeV is  $0.22 \mu b$ . As a result the yield is

$$Y = 0.48 \times 10^{-6}$$

for a 50cm hydrogen target and 100% geometric efficiency. Using a beam intensity of  $5 \times 10^5$  and 500 pulses per hour yields 125 events per hour ( $q^2 > 0.15$ ). We expect in 300 hours 37,500 pi-e events  $q^2 > 0.15$

$$115,000 \text{ pi-e events } q^2 > 0.1 (\text{GeV}/c)^2$$

$$10,000 \text{ k-e events } q^2 > 0.075 (\text{GeV}/c)^2$$

These event rates are reduced somewhat by efficiencies, radiative corrections and non-point-like behaviour but serve as a reasonable estimate. It also appears possible, if necessary, to use a target as long as 1m.

## APPARATUS REQUIREMENTS

UCLA

NAL

Magnetostrictive wire chambers

Liquid hydrogen target

Readout System

50 Kg-m magnet

HP 2100A Computer

Fast electronics

Interface

300 GeV unseparated negative beam

Scintillation and shower counters

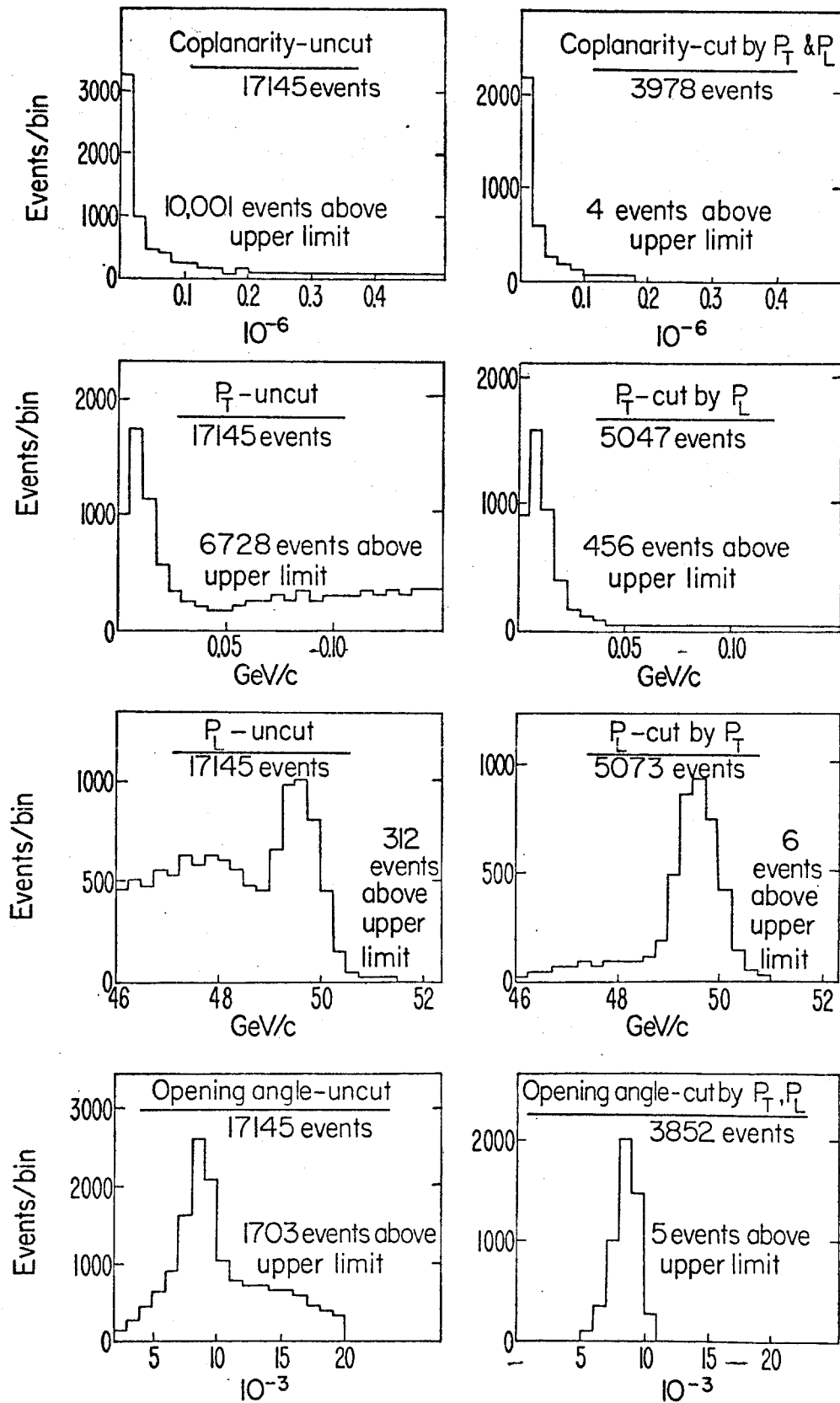


FIGURE 1

Distributions showing application of three constraints to 17,145 raw events leading to 3852  $\pi$ -e events.

# Experimental layout for pion-electron scattering

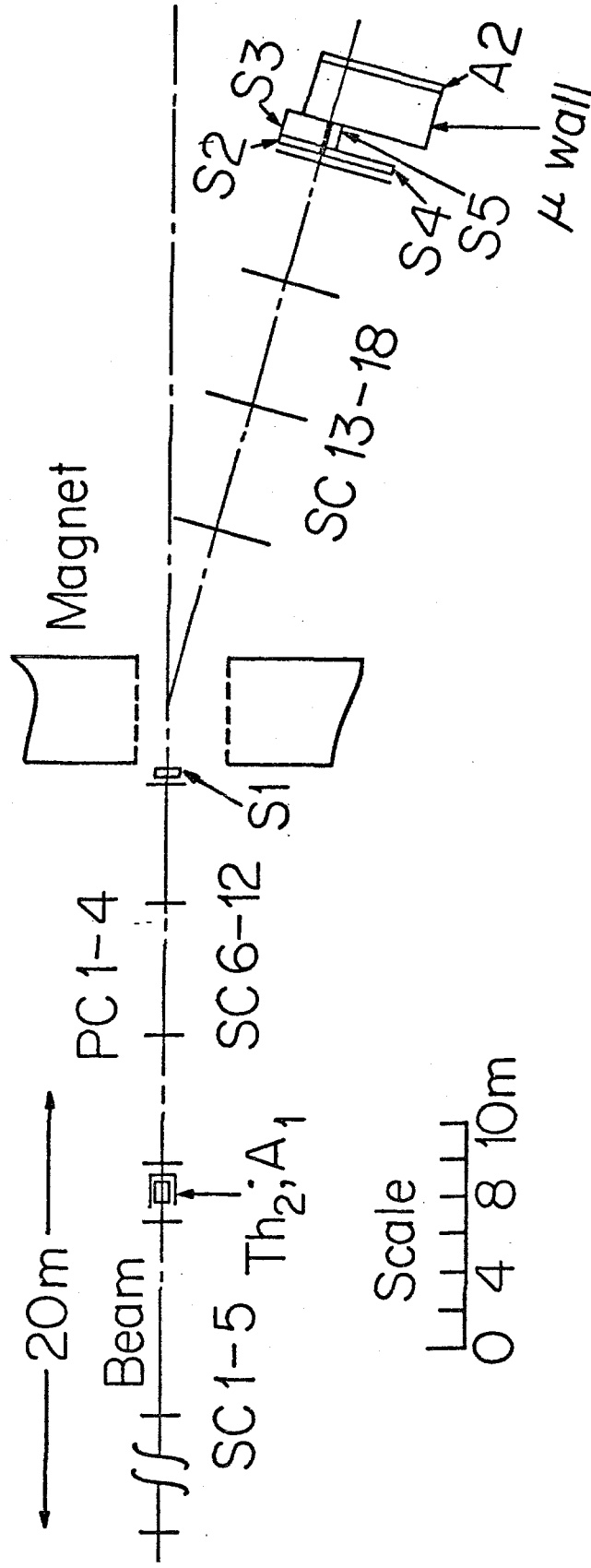


FIGURE 2

PC 1-4 are proportional chambers; SC 1-18 are magnetostrictive wire chambers;  $Th_2$  is the liquid-hydrogen target;  $A_1$  is the anti-coincidence counter for the target;  $S_1$  is a scintillator which defined the acceptance;  $S_2$  and  $S_4$  are scintillators which direct the pion and electron;  $S_3$  and  $S_5$  are shower counters;  $A_2$  is an anti-coincidence counter for muon rejection.

## APPENDIX 2 to Proposal 71

### Location of Experiment

#### I. Site

The hadron beam, N-5, to the 15' bubble chamber, is a suitable location for this experiment. The proposed position of the spectrometer is shown on Fig. 1. The spectrometer will extend downstream from the center of enclosure 113 approximately 80 meters. This arrangement requires that the two quadrupole magnets in enclosure 115 be removed and that the downstream pair of dipole magnets in enclosure 113 be moved upstream of the last string of quadrupoles. These modifications allow the hydrogen target to be located 1.5 meters inside enclosure 113. The BM109 magnets for the spectrometer will be located 25 meters downstream of the hydrogen target.

We emphasize that the proposed configuration is only one of several configurations acceptable to us in this general area. In particular, neutrino experts may object to having a large beam stop in front of their apparatus; if so, it may be possible to locate our beam stop behind the neutrino experiments. Another acceptable beam line could be formed by turning off the magnets in Enclosure 109, forming a new beam line parallel to the burm and locating pi-e scattering between the 30" and 15' bubble chambers. This solution would require devising some scheme to permit the beam to exit from the magnets in Enclosure 109. We feel that location of the experiment in the 30" beam line is unacceptable since the total bend in the pion beam is small.

## II. Beam requirements

There are several ways in which the necessary  $4 \times 10^5$  pions can be obtained using an incident beam of  $10^{11}$  protons.

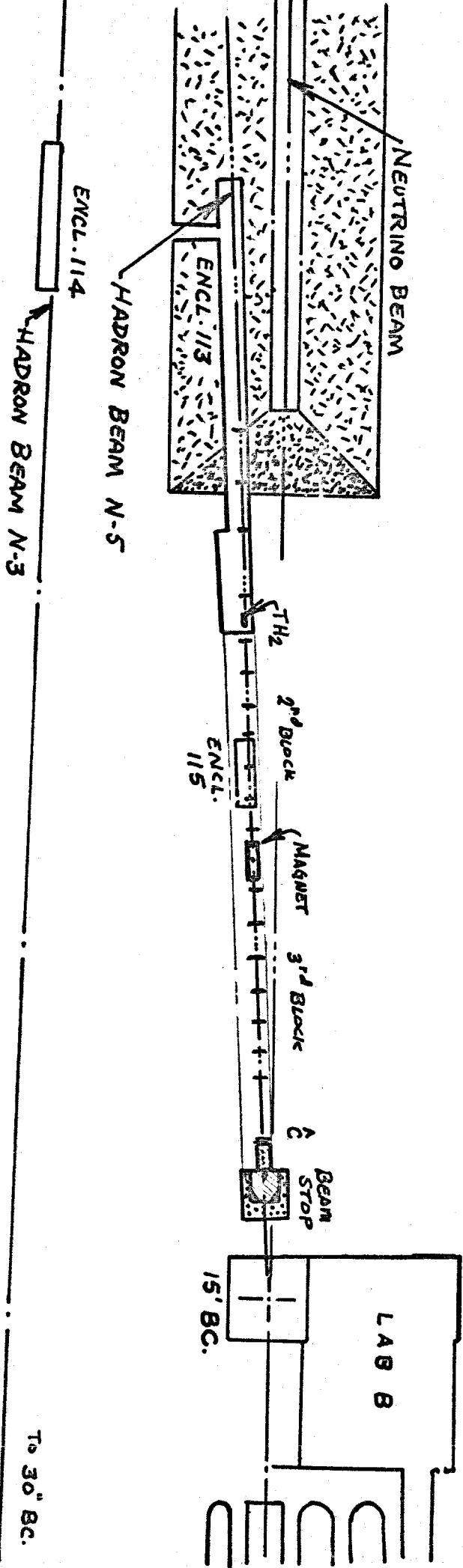
- a) Use the existing 30" target load
- b) Use the by-pass magnets upstream of the target load to deflect the beam around the load and target it in enclosure 100.
- c) Use the pions directly produced in the Cal Tech or muon load and simply transport them to our set up.
- d) It may be possible to use the proposed pulsed magnets to run simultaneously with the neutrino beam load(horn). In this mode a short high-current spill would be used to produce neutrinos, the magnets would then be pulsed, and a low current long spill would be sent down the by-pass and targetted in enclosure 100.

### III. Radiation Safety

The hadron safety requirements can be met with an iron beam dump eight feet in diameter and ten feet long (or a heavy concrete dump with dimensions two times larger), followed by six feet of concrete for neutron shielding. The  $10^4$  muons will be multiple-scattered by this dump; they can be bent down 8 mr by the spectrometer magnet, or the iron dump can be magnetized. In any case, the radiation problems due to the beam do not seem serious.

In order to obtain  $10^6$  pions in the beam (a factor 2.5 higher than was possible to use in the Serpukhov experiment), one needs to target  $\sim 10^{11}$  protons. If this is done in enclosure 100, some residual radiation problems will exist. Best estimates indicate that this will be the upper limit tolerable in this area.

The availability of a DISC-counter or perhaps even threshold counter in the hadron beam would allow us to collect 1000 kaon scatters in 200 hours, measuring the kaon radius to about 15%, simultaneously with the pi-e running. The long ( $\sim 1000$  meter) beam to this area makes doing the k-e experiment less favorable than discussed in Appendix I to proposal 71 although it is still feasible.



# PROPOSED $\pi$ -e SPECTROMETER LOCATION

